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OPTICS, HOLOGRAPHY AND MESOOPTICS IN BUBBLE CHAMBER OF VERTEX DETECTOR

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1. INTRODUCTION

The problem of construction of the bubble chamber of vertex detector of high spatial resolution has arisen after the discovery of particles with very small lifetime $\tau \sim 10^{-12} - 10^{-14}$s. To detect the decay of such shortlived particles with high efficiency the spatial resolution Δx must be set much smaller than the impact parameter B of the corresponding decay:

$$\Delta x \ll B \approx c\tau, \qquad (1)$$

where "c" is the velocity of the light[1]. For $\tau \sim 10^{-13}$s, we have $B \sim 30\ \mu m$ and $\Delta x \sim 5\ \mu m$. Until very recently only the nuclear emulsion technique with observation through optical microscope met this condition.

The depth of field attained by classical imaging optics for wave length $\lambda = 0.5\ \mu m$ is equal to

$$\Delta z \approx \frac{(\Delta x)^2}{\lambda} \sim 50\ \mu m \qquad (2)$$

and is very small relative to depth of bubble chamber of vertex detector amounting to $H = 10$ cm[1]. To detect the events over the whole depth of the bubble chamber there has been used holography instead of classical photography[2]. The first successful experiments with improved spatial resolution in the bubble chamber without the loss of depth of field have been performed in CERN[3]. The spatial resolution of 8 μm over the depth of field of 10 cm in the small heavy liquid bubble chamber has been obtained by means of the pulse holographic technique. The bubbles in tracks of 25 μm in diameter have been recorded with spatial resolution up to 2 μm[4]. In all these experiments the Gabor scheme [5] called "in-line holography" has been used.

On the reconstruction stage the hologram is illuminated by coherent light from CW He-Ne laser, and the real reconstructed image of bubbles is viewed through optical microscope by eye or is displayed on the TV screen[3]. In both cases the objective of the optical microscope has been used with small depth of view (2). During acquisition stage all the information contained on hologram must be scanned slice by slice. The number of such slices is as much as 10 cm/50$\mu m \approx 2 \cdot 10^3$.

2. IMAGING OPTICS

Let us treat the geometrical transformations which are performed by classical imaging optical system such as by a simple lens (Fig.1). In the geometrical optics approximation each point in the object space is transformed by lens into the point, which lies in the image space on the straight line going through the center of lens. The distance ℓ_2 from the center of lens to the imaged point is determined by expression

$$\ell_2^{-1} = f^{-1} - \ell_1^{-1}, \qquad (3)$$

where f is the focal length of lens and ℓ_1 is the distance from point to the center of lens. This transfromation is the one-to-one for all points the coordinates of which met the inequalities:

$$|z| > \ell_1, \qquad\qquad (4)$$
$$\left|\frac{x}{z}\right| < \Omega, \quad \left|\frac{y}{z}\right| < \Omega,$$

where Ω is the angular field of view of lens restricted by aberrations of lens.

The geometrical transformations, performed by simple lens, can be expressed as

$$\begin{aligned} 0D &\rightleftarrows 0D, \\ 1D &\rightleftarrows 1D, \\ 2D &\rightleftarrows 2D, \\ 3D &\rightleftarrows 3D. \end{aligned} \qquad (5)$$

Every point (zero-dimension space) goes into one point (zero-dimension space). Every line, straight or curved (one-dimension manifold), is transformed into the corresponding line (one-dimension manifold) in the image space. The convex or not-self-shaded surface (two-dimensional manifold) goes into the corresponding surface (two-dimensional manifold). We cannot detect the manifold of imaged points which are not laying in one plane by means of detector such as photoplate.

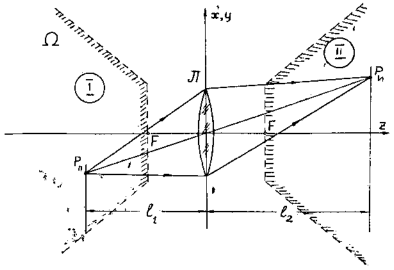

Fig.1. The formation of image of a point by means of lens Л in the geometrical optics approximation: I - the object space, II - the image space, $P_п$ - one of the points in the object space, $P_и$ - its image. The shaded region is that part of the whole space, the points of which are transformed by lens without noticed aberrations.

Mutual unambiguity of geometrical transformations (5) is lost partially or completely by diffraction of light. Due to finite value of wave length of the light each point from the object space is transformed by lens into the small 3D volume element in the image space. Its transversal dimensions are

$$\Delta x = \Delta y \sim \frac{\lambda}{a}, \qquad (6)$$

and longitudinal dimension is equal to

$$\Delta z \sim \frac{\lambda}{a^2} \qquad (7)$$

with

$$\mathrm{tg}\,a \approx a \approx \frac{R}{2f}, \quad a < 1, \qquad (8)$$

and R is the radius of the lens. From (6) and (7) for f =const we get

$$\sqrt{\lambda \Delta z} = \Delta x. \qquad (9)$$

If the value of $a = R/2f$ is diminished such that the radius of diffraction spot would be equal to the radius of lens, the lens can be removed without any remarkable deterioration of the image quality. Such an optical system is called a pinhole camera.

3. MESOOPTICS

The imaging system is called a mesooptical one if in the geometrical optics approximation every point of the object space is transformed into the straight line of finite or infinite length in the image space. The geometrical transformations performed by mesooptical imaging system can be written in the following form

$$\left.\begin{aligned} 0D &\rightarrow 1D \\ 1D &\rightarrow 2D \\ 2D &\rightarrow 3D \end{aligned}\right\} . \qquad (10)$$

The point goes into the straight line, the line goes into the surface, and the surface is transfromed into the 3D manifold.

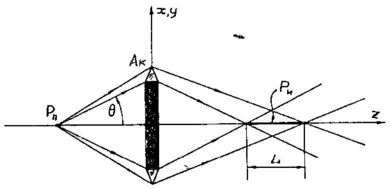

Fig.2. The formation of image of a point by means of circular conical axicon A_k: $P_П$ - one of the points in the object space, $P_И$ - the part of optical axis where the mesooptical image of the point $P_П$ is situated. The mean focal length of axicon is the function of angle θ.

The typical example of mesooptical imaging system is an axicon [6] with conical surfaces (Fig.2). Any point situated in the object space on the optical axis of axicon is transformed by axicon into the straight line of length L. The essential feature of axicon is that magnitude of L can assume practically any value in contrast to the classical imaging system where $L=0$ in all cases in the geometrical optics approximation and in the neglecting the aberrations of lens. The circular axicon is used not only in optics but also in acoustoscopy [7].

The diffraction of light in mesooptical system induces local spreading of every point in the transformed manifold. For example the extremities of finite straight line L are spread over the Δz and the transformed line goes into the figure of rotation, the transversal dimensions of which are equal by the order of magnitude to Δx and Δy from (6).

The second example of mesooptical system is circular diffraction grating [6] (Fig.3). The position and the magnitude of length L of straight line depends on the wave length λ on the period of grating "a" and on the external and internal diameters D_1 and D_2 of the circular diaphragm situated in the plane of circular diffraction grating.

The drawback of axicon and other axis symmetric mesooptical imaging system is that due to sivere aberrations of light in axicon the angular field of view is very small. Therefore such systems can be used only as a scanning imaging devices with detector of small dimensions on the optical axis. In contrast to this the concentrical mesooptical objectives have no restrictions on angular field of view. It will be recalled that concentrical is called the optical system consisting from spherical surfaces with common center of curvature [8]. According to fundamental theorem of geometrical optics [9] the concentrical objective, the example of which is shown in Fig.4, can contain only three or more spherical concentrical surfaces and cannot contain one or two spherical surfaces.

The situation in mesooptics is different. The mesooptical concentrical objective can contain only one or two spherical surfaces. The ray tracing in the simplest mesooptical objective

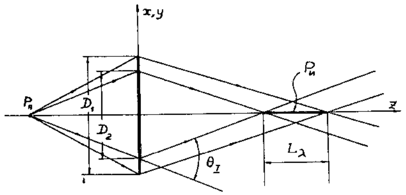

Fig.3. The formation of image of a point by means of circular diffraction grating in the first order diffraction of monochromatic light with wave length λ.

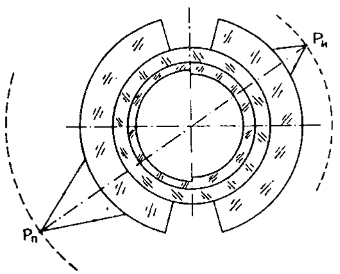

Fig.4. The cross section of concentrical objective with four spherical concentrical surfaces [8].

with only one spherical surface and with absorbing kern is shown in Fig.5. The classical concentrical objective which has been invented by Sutton in 1859 fails to find wide practical application due to its principally noncancelled drawback - the locus of imaging of point situated at equal length from the center of concentrical objective is forming a manifold situated on the spherical surface and cannot be detected on plane photofilm. In the case of mesooptical concentrical objective the image of high spatial resolution is filling the image space over high depth and therefore can be detected on plane film without using any diaphragm.

The drawback of any mesooptical concentrical objective is that it gives the image of low luminosity and low contrast. Therefore it can be usefully applied only for points or point-like objects. The chain of bubbles or streamers along the path of charge particle in the track chambers belongs to this class of objects.

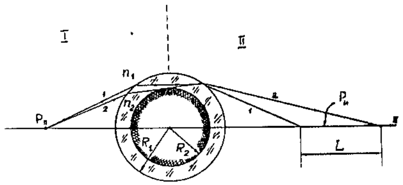

Fig.5. The simplest mesooptical concentrical objective with one spherical surface and absorbing spherical kern: $P_П$ a point in the object space I, $P_И$ - its mesooptical image in the image space II, n_1 - the refraction index of the surroundings, n_2 - the refraction index of spherical layer of external radius R_1 and internal radius R_2. The tracing of extreme rays is shown.

4. MESOOPTICS IN THE BUBBLE CHAMBER OF VERTEX DETECTOR

Let the registered event in the bubble chamber of vertex detector is detected by means of pulse holography [1-4]. On the stage of reconstruction the virtual bubble image is observed and is scanned with mesooptical objective according to the scheme shown in Fig.6. Two or more central projections of 3D image of tracks on the planes perpendicular to directions of projection are formed. 2D projections are read out by traditional devices and processed by the algorithms which are now used in the processing of stereo imaging in modern track chambers. The scanning depth L of mesooptical objective can be chosen either equal to total depth of chamber H or, if the track density on the hologram is very high, the scanning depth is diminished untill the reasonable observation condition is reached.

The information gathered on small area of photoplate by means of mesooptical objective represents the sum of intensity of object elements which are laying inside the conical tube of average diameter Δx and of length L. The analogous summing along the ray of transmitting radiation is accomplished in reconstructed tomography with X-ray [10] or with ultrasound [11]. The principal difference of mesooptics from reconstructed tomography is that the ray in mesooptics can be formed on finite length the value of which and its positioning in the object space can be varied by means of varying the parameters of mesooptical system. In the case of circular diffraction grating this aim is attained by varying the wave length of light and by changing the circular diaphragms.

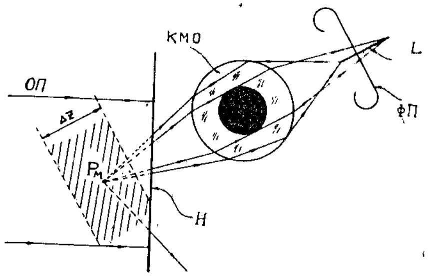

Fig.6. The mesooptical system of producing and detecting of one of central projections of the virtual image of tracks reconstructed from hologram by means of concentrical mesooptical objective: ОП - the illuminating beam of coherent light, H - hologram, P_M - virtual reconstructed image of one of bubbles, Δz - the depth of sharpness of mesooptical objective, L - the length of straight line, the part of which is the transformed virtual image of the bubble, ФП - photofilm. The tracing of rays shown in figure corresponds to formation of only one of two or more central projections.

5. MESOOPTICS IN NATURE

The typical example of mesooptics in nature is the gravitational lens [12, 13]. The rays of light going at the impact parameter ρ in the vicinity of star is deflected at the angle

$$\phi(\rho) = \frac{4GM}{c^2\rho}, \qquad (11)$$

where G is the gravitational constant [14]. We suppose that the gravitational radius of the nearest star

$$r_g = \frac{2GM}{c^2} \qquad (12)$$

is small relative to its geometrical radius R [15]. The smallest focal length of this natural mesooptical system is equal to

$$f_{min}(R, M) \cong \frac{R}{\phi(R)}. \qquad (13)$$

The observer situated on the straight line which connects the centers of two stars at distance $r > f_{min}(R, M)$ from the nearest star will see the far star in the form of ring around the nearest star with center coinciding with the center of the nearest star [12]. The gravitational lens (mesolens) produced by far galaxy has been discovered indeed [16].

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Сороко Л.М. Д1-82-642
Оптика, голография и мезооптика
в пузырьковой камере вершинного детектора

Показано, что проблема съема информации, возникшая при создании пузырьковой камеры вершинного детектора с высоким пространственным разрешением, может быть решена при помощи элементов мезооптики. Проведен анализ возможностей классической изображающей оптики и голографических систем в технике пузырьковых камер. Рассмотрены типичные примеры мезооптических изображающих систем. Описана схема применения мезооптики в системе съема информации с голограмм, регистрируемых в пузырьковой камере вершинного детектора с высоким пространственным разрешением. Отмечено, что гравитационная линза /мезолинза/ является типичной мезооптической системой.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Soroko L.M. D1-82-642
Optics, Holography and Mesooptics
in Bubble Chamber of Vertex Detector

It is shown that data acquisition problem in bubble chamber of vertex detector of high spatial resolution can be solved by introducing the mesooptical elements. There are treated the limitations of classical imaging optics and the new scopes of holographic systems in bubble chamber technique. The typical examples of mesooptical imaging systems are presented. The application of mesooptics in the system of scanning of holograms in bubble chamber of vertex detector of high spatial resolution is described. The gravitational lens (mesolens) can be considered as a typical mesooptical system.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1982